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Moisture buffer potential of experimental wall assemblies incorporating formulated hemp-lime



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ABSTRACT

Experiments were carried out according to the Nordtest protocol to study the moisture buffer potential of hemp-lime walls with a range of different internal linings and surface treatments. It was observed that the moisture buffer value was 'Excellent' when the inner surface of hemp-lime was exposed. 'Excellent' moisture buffer values were also obtained for hemp-lime with lime plaster. All other assemblies demonstrated 'Good' moisture buffer value. Moisture buffer values of the assemblies, after application of paint on the upper surfaces, were also determined. It was observed that application of synthetic pigment based trade paint could reduce the moisture buffer performance of the assembly consisting of hemp-lime and lime-plaster from 'Excellent' to 'Good' while between 61 and 69% reduction of moisture buffer value was observed for the other assemblies. However, the reduced buffer values of the assemblies are still comparable with other moisture buffering building materials. It was further observed that moisture buffer performance was improved when clay based organic paint was used instead of trade paint.

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1. Introduction

Hemp-lime is a bio-composite material comprised of hemp shiv, the woody core of hemp plant, and a lime based binder [1]. The composite can be cast into any rigid form and can be used as a floor, wall or roofing material. Hemp-lime is a carbon-negative and low embodied energy material [2,3]. Hemp shiv comes from renewable sources and lime is a flexible, reusable and breathable material with significantly lower embodied energy than conventional masonry materials [4]. Because of its low compressive strength [5–8], hemp-lime is typically used as an insulating infill material between structural framework [9].

Hemp-lime possesses excellent hygric and moderate thermal properties. The dry thermal conductivity of hemp-lime varies between 0.06 and 0.12 W/m K [1,10,11]. It is observed that the thermal performance of hemp-lime is better than what its U-value or thermal conductivity value suggests [4]. This is may be because of the low thermal diffusivity of hemp-lime resulting from its high specific heat capacity [12], varying between 1300 and 1700 J/Kg.K [3], combined with its high density, ranging between 220 and 950 kg/m³ [13]. Since the external boundary conditions are

dynamic, the high thermal mass of hemp-lime means that variations in changes in temperature can be dampened and the peak energy load can be reduced [14].

In terms of hygric properties, hemp-lime, like other cellulose materials [15], works as an effective hygric mass because of its 'Excellent' moisture buffer capacity in its exposed condition [16–18]. Moisture buffer capacity of a hygroscopic material enables the material to moderate the fluctuations in relative humidity of an enclosed space by utilising the adsorption and desorption properties of the material [19,20]. Moisture buffering properties of the material also helps to reduce condensation in the building envelope [21–24] and maintain indoor air quality [25,26]. In addition to the moisture buffer capacity, moisture buffer performance of a material depends also on the exposure area, vapour permeability, surface treatment of the material, moisture load [27,28], ventilation rate [28–32], volume rate [31] and initial humidity condition [33]. The moisture buffer value can be classified within the 'practical moisture buffer value classes', consisting of the following ranges: negligible, limited, moderate, good and excellent [19]. The moisture buffer value of exposed hemp-lime samples are reported as either 'Good' or 'Excellent' by a number of authors [16,17].

Moisture buffering can directly and indirectly reduce the energy consumption of buildings [34]. In terms of energy use, hygroscopic materials in general can reduce heating energy requirements by 2–3% and cooling energy requirements by 5–30% if integrated with

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a well-controlled HVAC system [34].

High thermal and hygric inertia of hemp-lime can potentially help to moderate the effect of temperature and relative humidity fluctuations in an interior space [35]. However, in practical applications, hemp-lime is used as a part of the building envelope system incorporating a combination of surface lining and surface treatment. The application of plaster or surface treated inner lining and the presence of a service void or air layer between the hemp-lime and the inner lining can potentially influence the moisture buffering ability of hemp-lime since the material is no longer in direct contact with the interior boundary conditions. Furthermore, use of coating or inner layers may delay and reduce vapour diffusion [36]. The aim of the present study is to compare the moisture buffer values of vapour-open wall assemblies containing hemp-lime and inner linings and surface treatments with that of the exposed hemp-lime. The Nordtest [9] protocol is followed to determine the moisture buffer values of the assembly. The experiments described in this article are part of the experiments being carried out in the EPSRC-funded HIVE building situated in the Building Research Park at Wroughton, UK.

2. Theory

2.1. Moisture buffer capacity

Moisture buffer capacity is a hygric property by which hygroscopic materials in touch with surrounding air adsorb and desorb moisture to create equilibrium with the relative humidity of the surrounding space. A number of methods are available to determine moisture buffer capacity such as the Nordtest protocol [19], the Japanese Standards [37], the ISO standard [38], the method proposed by Padfield [39] and the Ultimate Moisture Buffer Value concept [40]. Among those, Nordtest method is the pioneering method and is mostly used in the European context. The Nordtest protocol expresses moisture buffer capacity in following three ways:

2.1.1. Moisture effusivity

Moisture effusivity (b_m) is the measure of the ability of the material to exchange moisture with its surroundings when the surface of the material is exposed to sudden change in humidity [19]. The equation for moisture effusivity is:

$$b_m = \sqrt{\frac{\delta_p \cdot \rho_0 \cdot \frac{\partial u}{\partial \phi}}{P_s}} \quad (1)$$

where, b_m is moisture effusivity [$\text{kg}/(\text{m}^2 \cdot \text{Pa} \cdot \text{s}^{1/2})$], δ_p is water vapour permeability [$\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$], ρ_0 is the dry density of the material (kg/m^3), u is moisture content (kg/kg), ϕ is relative humidity (-), P_s is saturation vapour pressure (Pa).

2.1.2. Ideal moisture buffer value (MBV_{ideal})

Ideal Moisture Buffer Value is the theoretical determination of moisture buffer value (MBV) based on its moisture effusivity, time period of moisture uptake and saturation vapour pressure. Ideal Moisture Buffer Value expresses the upper limit of the moisture buffer capacity [41]. The equation for Ideal Moisture Buffer Value is,

$$MBV_{ideal} \approx \frac{G(t)}{\Delta RH} = 0.00568 \cdot b_m \cdot P_s \cdot \sqrt{t_p} \quad (2)$$

where $G(t)$ is accumulated moisture uptake (kg/m^2) and the corresponding moisture release during a time period t_p (s). The ideal moisture buffer value is measured in [$\text{g}/(\text{m}^2 \cdot \% RH)$].

2.1.3. Practical moisture buffer value ($MBV_{practical}$)

Practical moisture buffer value, $MBV_{practical}$, is defined as the amount of moisture content that passes through the unit open surface of the material when the material is exposed to variation in relative humidity of the surrounding air. MBV can be expressed as [42]:

$$MBV_{practical} = \frac{\Delta m}{A \cdot (RH_{high} - RH_{low})} \quad (3)$$

where $MBV_{practical}$ is practical moisture buffer value [$\text{g}/(\text{m}^2 \cdot \% RH)$], Δm is moisture uptake/release during the period (g), A is open surface area (m^2), $RH_{high/low}$ is high/low relative humidity level (%). For the present study, $MBV_{practical}$ values of hemp-lime assemblies are determined.

2.1.4. True moisture penetration depth

The true moisture penetration depth (also described as 'moisture penetration depth'), $d_{p1\%}$, is the depth at which the amplitude of moisture variation is 1% of the variation on the surface of the material [19,41,43] and is expressed as,

$$d_{p1\%} = 4.61 \cdot \sqrt{\frac{D_w \cdot t_p}{\pi}} \quad (4)$$

where D_w (m^2/s) is the moisture diffusivity and is expressed as,

$$D_w = \frac{\delta_p P_s}{\rho \xi_u} \quad (5)$$

where ξ_u is the specific moisture capacity (kg/kg) and expressed as,

$$\xi_u = \frac{\partial u}{\partial \phi} \quad (6)$$

2.1.5. Moisture buffer classes

In addition to the direct comparison of moisture buffer values of the assemblies, moisture buffer capacity of the materials can also be categorised in terms of their moisture buffer classes [19]. As shown in Fig. 1, the moisture buffer values of the materials are classified in to following categories: Negligible (MBV: 0.0–0.2), Limited (MBV: 0.2–0.5), Moderate (MBV: 0.5–1.0), Good (MBV: 1.0–2.0), Excellent (MBV: 2.0-upwards).

2.2. Vapour diffusion resistance factor

Moisture transfer occurs through porous materials when there is vapour pressure difference between two opposite surfaces. Fick's law [44] expresses isothermal moisture transfer by the following equation:

$$g_v = -\delta \cdot \nabla \rho_v \quad (7)$$

where g_v is the vapour/moisture flux [$\text{kg}/(\text{m}^2 \cdot \text{s})$], δ is the vapour permeability of the porous system in the material [$\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$], ρ_v is the water vapour partial pressure (Pa).

Vapour diffusion resistance factor of a material, μ , is the ratio of vapour permeability of air and the material. The equation for the vapour diffusion resistance factor is expressed as:

$$\mu = \frac{\delta_a}{\delta} \quad (8)$$

where μ is the vapour diffusion resistance factor (-), δ_a is the vapour permeability of air [$\text{kg}/(\text{m} \cdot \text{s} \cdot \text{Pa})$].

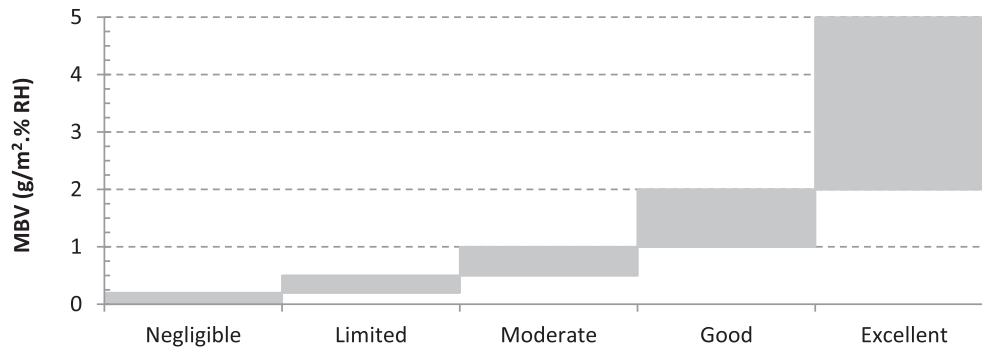


Fig. 1. Moisture buffer classes.

Vapour permeability δ is calculated from the following expression:

$$\delta = W \cdot d \quad (9)$$

where W is the water vapour permeance [$\text{mg}/(\text{m}^2 \cdot \text{h} \cdot \text{Pa})$] and d is the test specimen thickness (m). W is determined from the following expression:

$$W = \frac{G}{A \cdot \Delta p} \quad (10)$$

where A is the surface area of the specimen (m^2) and Δp is the pressure difference (Pa).

2.3. Adsorption-desorption isotherm

An adsorption isotherm is the constant temperature relationship between the amounts of adsorbate accumulated by a unit quantity of adsorbent in equilibrium condition in a range of partial pressures [45]. A desorption isotherm expresses the similar relationship when equilibrium is reached by desorption.

3. Materials and assembly

3.1. Material preparation

3.1.1. Hemp-lime

The hemp-lime is formulated from hemp shiv, hydraulic lime, a rapid setting additive and water. The formulation of hemp-lime is shown in Table 1 and the weight of the constituents of the hemp-lime mix in the panel is shown in Table 2. The lime plaster, used later in the assembly preparation, consists of hydraulic lime and plastering sand with the weight based ratio of 1:5.

To prepare the samples, hemp, lime and the additive were mixed in a pan type concrete mixer and water was added slowly until a uniform mix was attained. Depending on the amount of the constituents, the mixing process may take between 7 and 10 min. The mix was then cast into a wooden mould with the inner dimension of $400 \text{ mm} \times 400 \text{ mm} \times 120 \text{ mm}$. The mould was internally divided by 2 mm cardboard partitions to create 16 individual moulds with the dimensions of $98 \text{ mm} \times 98 \text{ mm} \times 120 \text{ mm}$. One surface of the wooden moulds was then exposed to 200 Pa air

Table 2

The weight of the constituents of the hemp-lime mix in the panel.

	Hemp (kg)	Lime (kg)	Rapid setting additive (kg)	Water (kg)
Mix/mould	2.7	3	0.24	6.4

pressure in an air-drying rig at the ambient temperature of $23 \pm 2^\circ \text{C}$ for 16 h, a new drying method developed within the EU funded Hempsec project [46], which aims to expand the market for a pre-fabricated, pre-dried panelised system of hemp-lime construction. The average dry density of hemp-lime was 290 kg/m^3 . The buffer test started 3 weeks after the drying of the samples.

3.1.2. Lining materials

The constituents and dry densities of the lining and finishing materials are provided in Table 3.

3.2. Assembly preparation

Ten variations of hemp-lime assemblies were prepared for the test (Fig. 2). Further variations are prepared by applying trade paint on the surfaces of some of these ten variations to study the effect on moisture buffering of applying the trade paint finish. For the paint finish, a water based white matt emulsion was used. The assemblies are briefly described below:

- **HL:** The base case assembly with exposed hemp lime (HL) surface.
- **HL + Plaster:** 15 mm lime plaster (Plaster) is added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + Plaster + Paint.
- **HL + Air + PB:** 25 mm air gap (Air) and 12.5 mm paper backed gypsum plaster board (PB) are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + Air + PB + Paint.
- **HL + Air + PB + Plaster:** 25 mm air gap, 12.5 mm paper backed gypsum plaster board and 15 mm lime plaster are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + Air + PB + Plaster + Paint.
- **HL + BM:** Breather membrane (BM) is added to the exposed surface of the base case hemp-lime.

Table 1

Weight based ratio in the hemp-lime mix.

Binder/Hemp (%)	Water/Hemp (%)	Rapid setting additive/total binder content (%)
1.2	2.375	7.5

Table 3
Properties of lining materials and paints.

Materials	Constituents	Thickness (mm)	Dry density (Kg/m ³)
Plasterboard	Gypsum, paper	12	670
Wood Wool Board 1	Shredded wood, cement	15	460
Wood Wool Board 2	Shredded wood, magnesite	23	455
Trade Paint		N/A	N/A
Organic paint	Clay, chalk, talc, casein, borax, kaolin, titanium dioxide, cellulose fibre, gum arabic.	N/A	N/A

- **HL + BM + Air + PB:** Breather membrane, 25 mm air gap and 12.5 mm paper backed gypsum plaster board are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + BM + Air + PB + Paint.
- **HL + BM + Air + PB + Plaster:** Breather membrane, 25 mm air gap, 12.5 mm paper backed gypsum plaster board and lime plaster are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + BM + Air + PB + Plaster + Paint.
- **HL + WWB1 + Air + PB:** 12.5 mm Wood Wool Board (WWB), 25 mm air gap and 12.5 mm paper backed gypsum plaster board are added to the exposed surface of the base case hemp-lime.
- **HL + BM + WWB1 + Air + PB + Plaster:** Breather membrane, 12.5 mm Wood Wool Board1, 25 mm air gap, 12.5 mm paper backed gypsum plaster board and lime plaster are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + BM + WWB1+Air + PB + Plaster + Paint.
- **HL + BM + WWB2+Air + PB + Plaster:** Breather membrane, 12.5 mm Wood Wool Board2, 25 mm air gap, 12.5 mm paper backed gypsum plaster board and lime plaster are added to the exposed surface of the base case hemp-lime. The following variation is also tested: HL + BM + WWB2+Air + PB + Plaster + Paint.

Table 4 shows the assemblies with their assigned names.

4. Method

4.1. Moisture buffer value

The samples were sealed on 5 out of 6 sides with aluminium foil tape. The upper surfaces of the assemblies were kept exposed for adsorption and desorption of moisture. The assemblies were then conditioned to 23 °C temperature and 50% relative humidity to reach equilibrium moisture content in a climate chamber.

The test assemblies were exposed to 75% relative humidity for 8 h and 33% relative humidity for 16 h in the climate chamber in accordance with the Nordtest Protocol. In each cycle, mass of the assemblies were measured at the end of each exposure using an analytical weighing scale with a resolution of 0.1 g. Change in moisture mass, Δm , was determined as the average of the weight gain during the moisture uptake phase of the cycle, and the weight loss during moisture release. The MBV was calculated as mass change, Δm , per m² and per ΔRH (relative humidity), based on the mean of last three cycles once dynamic equilibrium was attained. The dynamic equilibrium was considered to be attained when the change in mass, Δm (g), was less than 5% between the last three cycles [19].

Two tests were carried out. During the first test, moisture buffer value of all the samples were measured as the base case samples, before adding any layers, plasters or surface treatment. During the second test, moisture buffer values of the assemblies were measured. The routinely recorded spot measurement of air velocity with a hot-wire anemometer showed that the air velocity over the

surface of the samples varied between 0.15 m/s to 0.2 m/s.

The sorption kinetics, the plot of moisture uptake/release versus time from which the rate of sorption can be determined, of the following assemblies was also determined during the relative humidity cycles: Assembly 1, Assembly 2_Paint, and Assembly 10_Paint.

4.2. Vapour diffusion resistance factor

The vapour diffusion resistance factor of the samples were determined according to the British Standard BS EN 12086 [47]. The samples were initially conditioned at (23 ± 2) °C temperature and $(50 \pm 5)\%$ relative humidity to reach a constant mass. The specimens were placed on glass dishes containing desiccant and salt solutions for the dry cup and wet cup test, respectively. The sides of the insulations were sealed with wax with aluminium foil on top to achieve unidirectional moisture flow. For the dry cup test, the relative humidity inside the dishes was 0% and outside the dishes was $50 (\pm 3)\%$. For wet cup test, the relative humidity inside the dishes was $50 (\pm 3)\%$ and outside the dishes was $93 (\pm 3)\%$. The test assembly was then conditioned in a climate chamber for 24 h. The differential of partial vapour pressure between 'in the atmosphere' and 'in the test assembly' drives the vapour through the specimen. The assemblies were weighed at every 24 h until five successive determinations of change in mass per unit time for each specimen was $\pm 5\%$ of the mean value. The vapour diffusion resistance factor, μ , was calculated using Eq. (7).

4.3. Adsorption-desorption isotherm

Two methods used for determining adsorption isotherm are discussed below.

4.3.1. Dynamic vapour sorption (DVS)

The DVS system is a recording microbalance capable of measuring changes in sample mass lower than 1 part in 10 million. The sample is hung from a microbalance in a sample pan. Air carrying the test vapours is then passed over the sample at a defined flowrate and temperature. The sample mass readings from the microbalance then reveal the vapour adsorption/desorption behaviour of the sample. The DVS instrument was used to determine the adsorption–desorption isotherm and hysteresis of hemp-lime and the other component materials at 23 °C temperature and the relative humidity ranges of 0%–95%.

4.3.2. Gravimetric method

The British Standard BS EN ISO 12571 [48] is used for gravimetric determination of the adsorption isotherm. Three samples of the dimension of 100 mm × 100 mm with a thickness of 120 mm are dried to reach constant mass. To determine the adsorption isotherm, the samples are consecutively exposed to eleven increasing relative humidity steps between 10% and 98% while keeping the temperature constant at $23 (\pm 0.5)$ °C in a climate chamber. It should be noted that 98% relative humidity was not achievable in the DVS instrument, so 95% relative humidity was

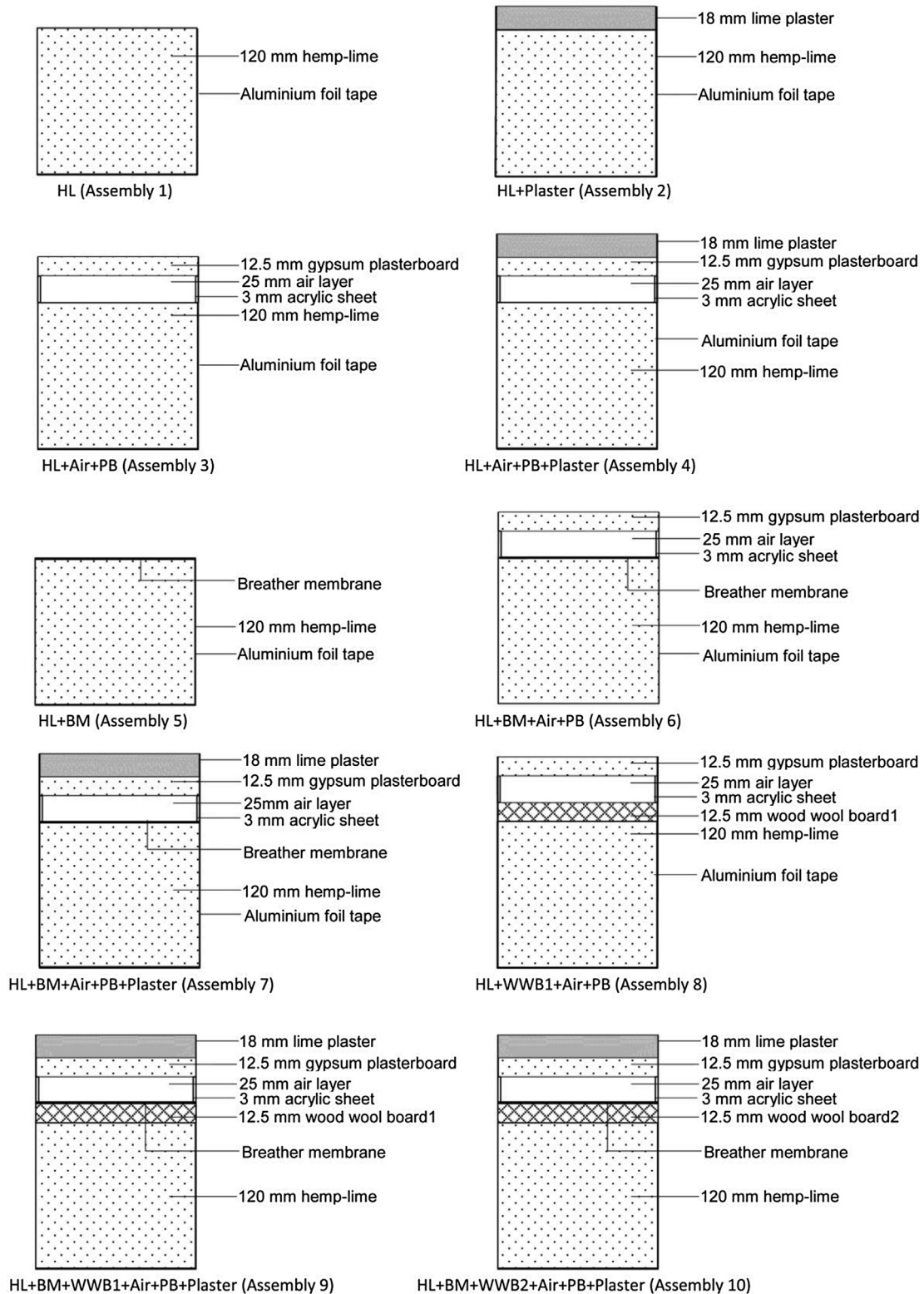


Fig. 2. Hemp-lime assemblies.

also included in the gravimetric test for the purpose of comparison. The process was carried out in reverse order, in seven decreasing steps due to the time constraint, to determine the desorption isotherm. During each exposure, the samples were required to reach equilibrium moisture content (EMC) according to BS EN 12429 [49]. The adsorption/desorption of moisture content by

weight U (kg/kg) was calculated as follows:

$$U = \frac{m - m_0}{m_0}$$

Where, m_0 is the mass of the material at dry condition (kg) and m is

Table 4
The assemblies with the symbolic names.

Assemblies	Symbol
HL	Assembly 1
HL + Plaster	Assembly 2
HL + Plaster + Paint	Assembly 2 (Paint)
HL + Air + PB	Assembly 3
HL + Air + PB + Paint	Assembly 3 (Paint)
HL + Air + PB + Plaster	Assembly 4
HL + Air + PB + Plaster + Paint	Assembly 4 (Paint)
HL + BM	Assembly 5
HL + BM + Air + PB	Assembly 6
HL + BM + Air + PB + Paint	Assembly 6 (Paint)
HL + BM + Air + PB + Plaster	Assembly 7
HL + BM + Air + PB + Plaster + Paint	Assembly 7 (Paint)
HL + WWB1+Air + PB	Assembly 8
HL + WWB1+BM + Air + PB + Plaster	Assembly 9
HL + WWB1+BM + Air + PB + Plaster + Paint	Assembly 9 (Paint)
HL + WWB2+BM + Air + PB + Plaster	Assembly 10
HL + WWB2+BM + Air + PB + Plaster + Paint	Assembly 10 (Paint)

the mass of the material at the equilibrium moisture content at any relative humidity (kg).

5. Result and discussion

5.1. Practical moisture buffer value

5.1.1. Assemblies without paint

The moisture buffer values of the assemblies are presented in Fig. 3 and the percentage decrease of moisture buffer value

compared to the base case is presented in Fig. 4. The kinetics of sorption of some of selected samples are presented in Fig. 5. For the kinetics, sampling frequency was 1 min and the data are presented as a running average of every 30 min. An overall observation of the moisture buffer values of the assemblies indicates that the exposed Assembly 1 and Assembly 2 demonstrate 'Excellent' moisture buffer value whereas all other assemblies demonstrate 'Good' moisture buffer value. However, a higher standard deviation from the mean moisture buffer value is observed in the base case hemp-lime than in the hemp-lime with lime plaster. The inhomogeneous surface of the unexposed hemp-lime may lead to air gaps between the aluminium foil and the unexposed hemp-lime surfaces. This, combined with the potentially differing surface resistance due to the inhomogeneity and the variation in the air velocity within the range of 0.5 m/s over the surfaces, can plausibly contribute to the variations in moisture buffer values. Once the exposed hemp-lime surface is covered with homogenous lime plaster, the standard deviation from the mean is reduced.

While the decrease of 61–69% moisture buffer value from that of the base case is significant, the moisture buffer value of the assemblies are still within the range of 'Good' moisture buffer classes and are comparable to the moisture buffer values of the following conventional materials, as reported in the Nordtest round robin tests [19]: exposed spruce, exposed birch panel, exposed brick, exposed laminated wood and exposed concrete (Fig. 6).

5.1.2. Assemblies with paint

In practical applications, the inner linings of the surfaces are usually coated with paint and can influence the moisture buffering

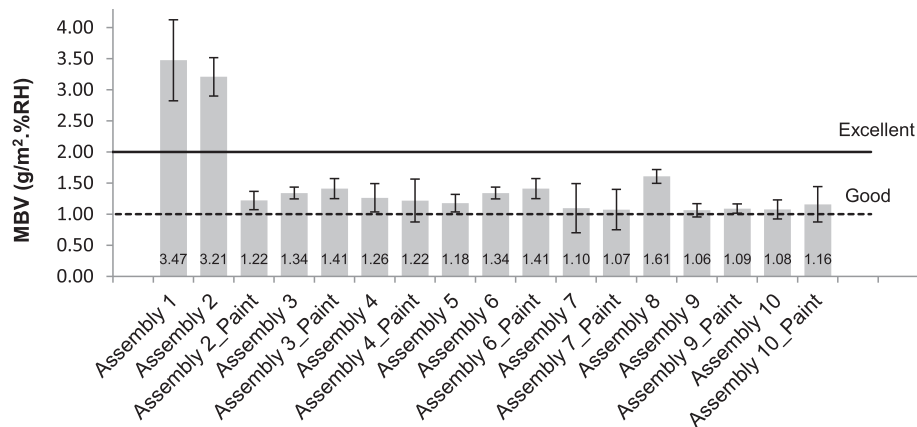


Fig. 3. Moisture buffer value of the assemblies.

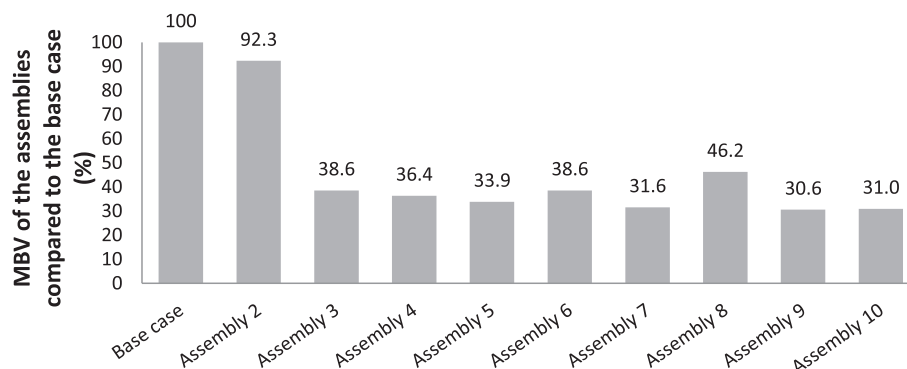


Fig. 4. Decrease in moisture buffer value of the assemblies compared to the base case hemp-lime.

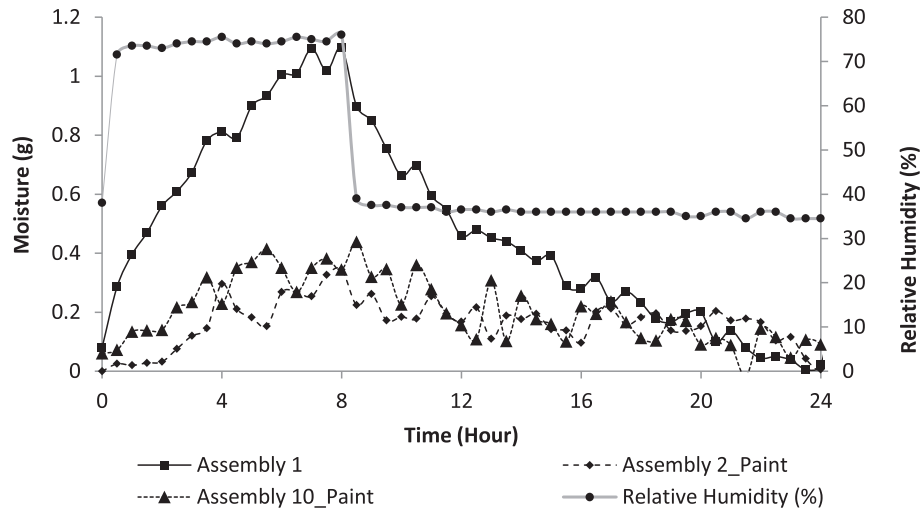


Fig. 5. Kinetics of sorption during a stable single buffer cycle.

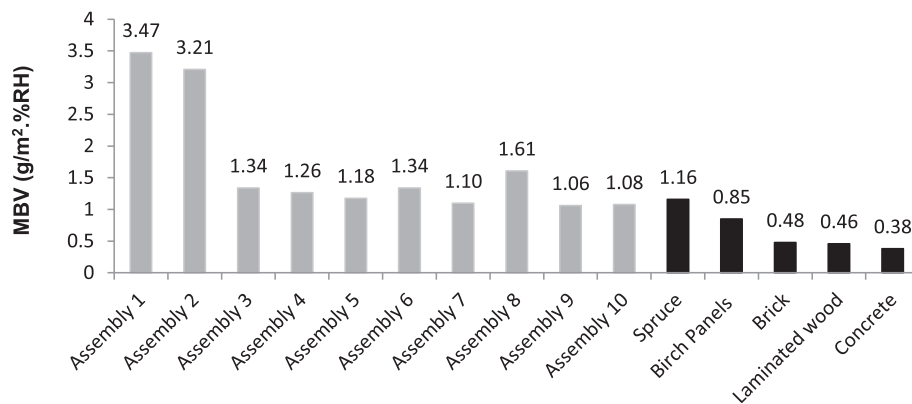


Fig. 6. MBV of the hemp-lime assemblies compared to other materials.

ability of the coating [50,51] and therefore, of the hygroscopic layer behind it. The impact of the application of trade emulsion paint on the surface of the assembly is presented in Fig. 3. The results show that the application of trade paint on the surface of the assemblies decrease the MBV value of Assembly 2 by 62%, Assembly 4 by 3.6%, Assembly 7 by 2.2% and increased the MBV values of Assembly 3 by 5.2%, Assembly 6 by 5.4%, Assembly 9 by 2.8% and Assembly 10 by 7.6%. Except for Assembly 2, the changes in the MBV values as a result of applying paints are not significant. The MBV value of all the painted assemblies still remains within the classification of ‘Good’ MBV as in the case of the assemblies without paint. It is plausible that the synthetic pigments of the water based emulsion paint affects the vapour permeability of lime plaster and paper backed plasterboard at different magnitudes by modifying the surface porosity of the materials. With the assumption that Assembly 2 would perform better with organic paint, clay paint was applied on the exposed surface of an unpainted Assembly 2 and the moisture buffer value was determined. The moisture buffer value was 1.87, a 54% increase from the similar assembly with trade paint (Fig. 7).

5.2. Practical moisture buffer value of the individual materials

In assembly 3 to assembly 10, different layers of component materials were added to the base case assembly as stated in Table 3. The MBV values of these added materials may contribute to the

MBV of the assemblies. To assess the contribution of the added materials to the MBV of the assemblies, the MBV of the following component materials were also obtained: Plasterboard (PB), Wood Wool Board1 (WWB1) and Wood Wool Board2 (WWB2). The result is shown in Fig. 8.

The contribution of plasterboard, in the assembly where plasterboard is the only added material, can be assessed by comparing the MBV values of PB and Assembly 3 (Fig. 9). It can be observed that the MBV value of Assembly 3 is 103% higher than that of the PB, confirming that the hemp-lime in the assembly is actively involved in the moisture buffering of the composite assembly. In terms of assessing the moisture activity of WWB1, it can be observed that the MBV of Assembly 8 is 20% lower than the MBV of WWB1 which

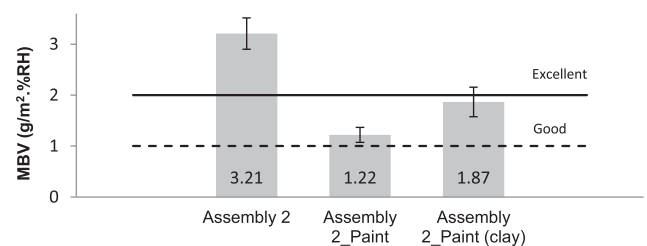


Fig. 7. Effect of paints on Assembly 2.

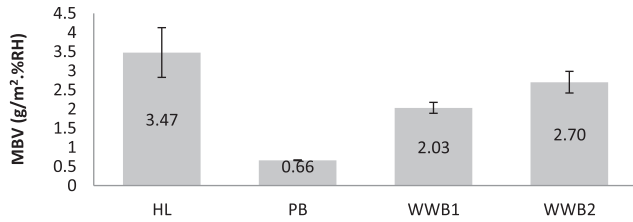


Fig. 8. MBV of PB, WWB1 and WWB2 compared to the base case HL.

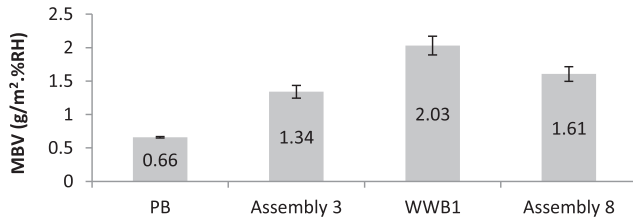


Fig. 9. MBV of Assembly 3 and Assembly 8 compared to PB and WWB1, respectively.

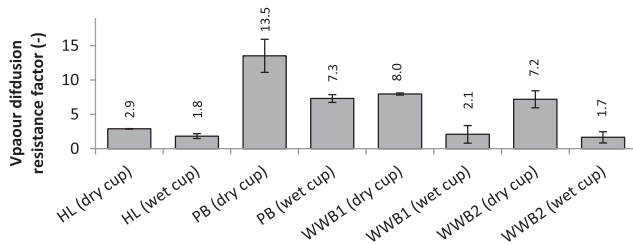


Fig. 10. Vapour diffusion resistance factor of HL, PB and WWB1, and WWB2.

implies that hemp-lime may not be fully participating in the moisture buffering of the assembly. In addition to the high MBV of WWB1, the reason for this can be partially attributed to the

comparative vapour diffusion resistance factors of PB, WWB1 and hemp-lime. The vapour diffusion resistance factor of the component materials is discussed in Section 5.3.

5.3. Vapour diffusion resistance factors of the individual materials

The vapour diffusion resistance factor, μ , of HL, PB, WWB1, and WWB2 was determined in both dry cup and wet cup tests. The results are shown in Fig. 10.

For the dry cup test, the vapour diffusion resistance factor of PB is 69.8% higher than that of WWB1 and the vapour diffusion resistance factor of WWB1 is 172.9% higher than that of hemp-lime. For the wet cup test, the vapour diffusion resistance factor of PB is 249.3% higher than that of WWB1 and the vapour diffusion resistance factor of WWB1 is 14.3% higher than that of hemp-lime. This, combined with the effect of the thickness of PB, air layer and WWB, will potentially decrease the effective moisture penetration depth of hemp-lime and will affect the overall MBV of the assembly.

5.4. Adsorption-desorption isotherm

5.4.1. Dynamic vapour sorption method

The adsorption-desorption isotherm (Fig. 11) of hemp-lime and the other component materials was determined at 23 °C temperature using the DVS equipment.

5.4.2. Gravimetric method

The adsorption isotherms of hemp-lime, wood wool board and plasterboard (Fig. 12) were also determined by the gravimetric method using a climate chamber following the methodology presented in subSection 4.3.

For plasterboard, considerable difference is noted between the isotherms determined by DVS and gravimetric method. For the gravimetric method, both sides of the plasterboard contained paper while small samples of plasterboard without any paper backing were tested in the DVS instrument. It follows that the two methods of test are not directly comparable, as the paper lining has a high moisture sorption capacity which was not included in the DVS

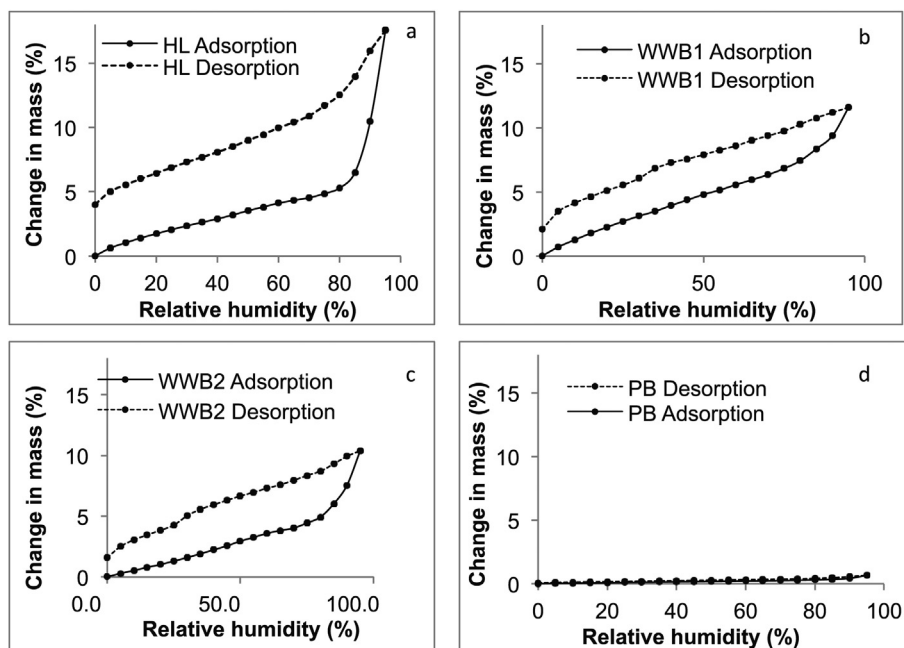


Fig. 11. Adsorption-desorption isotherm of (a) hemp-lime, (b) WWB 1, (c) WWB 2, (d) PB, determined in a DVS instrument.

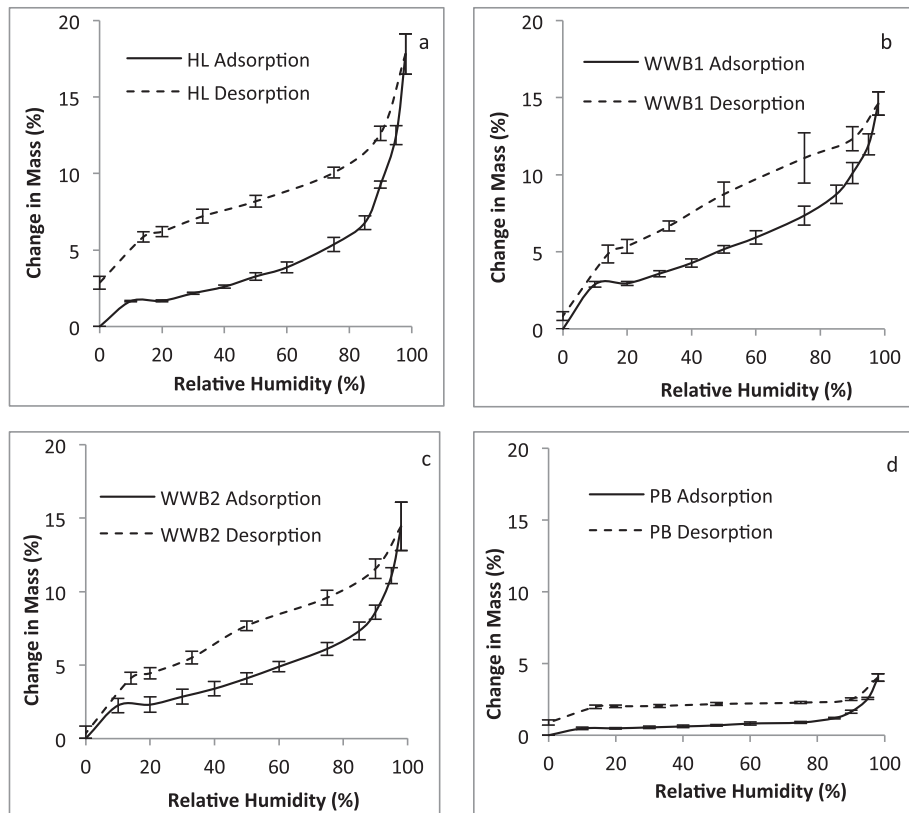


Fig. 12. Adsorption-desorption isotherm of hemp-lime and component materials, determined by gravimetric method.

testing method. The density and porosity of the samples may also vary for these two methods.

5.5. Ideal moisture buffer value and true moisture penetration depth

The ideal moisture buffer value and the moisture penetration depth of hemp-lime, WWB1, WWB2 and PB were calculated using Eqs. (3) and (4), respectively. Because of the hysteresis between the relative humidity ranges of 33%–75%, ∂u was taken as an average of

the adsorption and desorption curves. The practical moisture buffer value and the ideal moisture buffer value are presented in Fig. 13. The true moisture penetration depth and actual thickness of the materials are presented in Fig. 14.

It can be observed in Fig. 14 that the moisture penetration depth of hemp-lime is smaller than the thickness of the system under test. It is plausible that the moisture buffer potential of hemp-lime will be fully utilised when the material is exposed to the relative humidity cycle. On the other hand, the moisture penetration depth of WWB1, WWB2 and PB are greater than their thickness in the

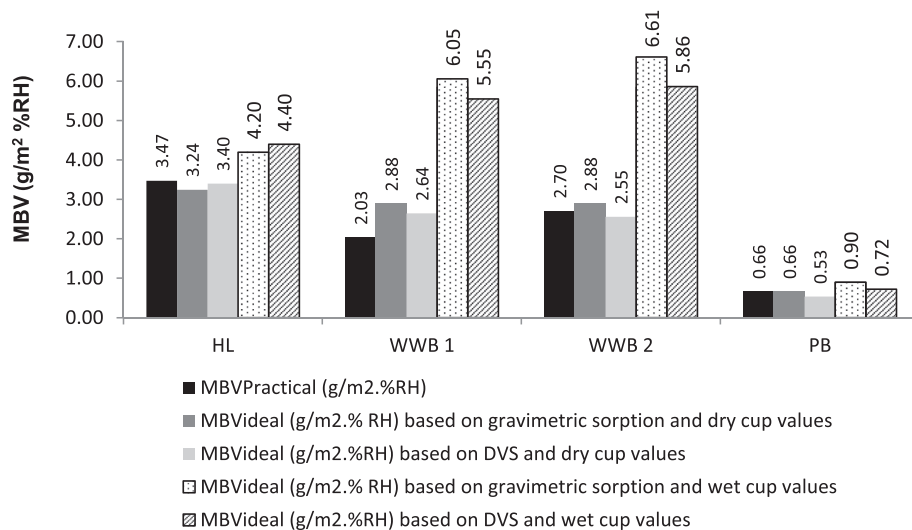


Fig. 13. The ideal and practical moisture buffer value of HL, WWB1, WWB2 and PB.

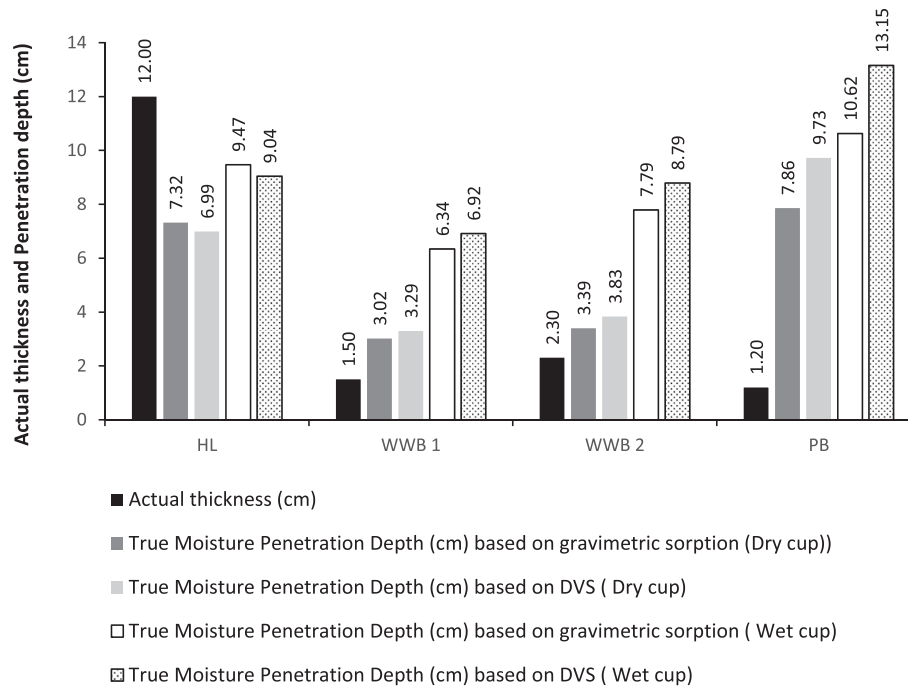


Fig. 14. The moisture penetration depth and effective thickness of HL, WWB1, WWB2 and PB.

system. It means that, while the moisture buffer value of those may not be fully utilised, moisture will penetrate through these materials to the next layer. However, the high vapour diffusion resistance factor of plasterboard will potentially affect the moisture buffer value of the lower layers.

The experimental assessment of the moisture penetration depth of hemp-lime was also carried out. Two samples of hemp-lime with 7 cm and 12 cm thickness were covered in five sides with aluminium foil tape. A temperature and relative humidity sensor was placed between the lower surface and the aluminium foil tape. The sensors were exposed to the cyclic moisture profile following the Nordtest protocol. It was observed (Fig. 15) that the amplitudes of relative humidity variation at 7 cm and 12 cm are 23.07% and 0.28%, respectively, of the amplitudes of relative humidity variation at the surface. At the true moisture penetration depth, the amplitude of variation of relative humidity should be 0.37%. When

compared in terms of vapour pressure, the variations are 70% and 6% at 7 cm and 12 cm, respectively. Therefore, it is plausible that the moisture penetration depth of the formulated hemp-lime is higher than 7 cm and closer to 12 cm.

6. Conclusion

Experiments were carried out to determine the effect of adding different inner layers and coatings to the base case hemp-lime on the MBV of the assemblies. It is observed that, except for the application of lime plaster on hemp-lime, adding inner layers reduces the MBV of hemp-lime significantly. The reduced MBV values still remain within the range of 'Good' buffer class. To study the contribution of individual layers to the MBV of the assemblies, the MBV values of plaster board and wood wool boards are also determined. It is observed that moisture buffer capacity of hemp-

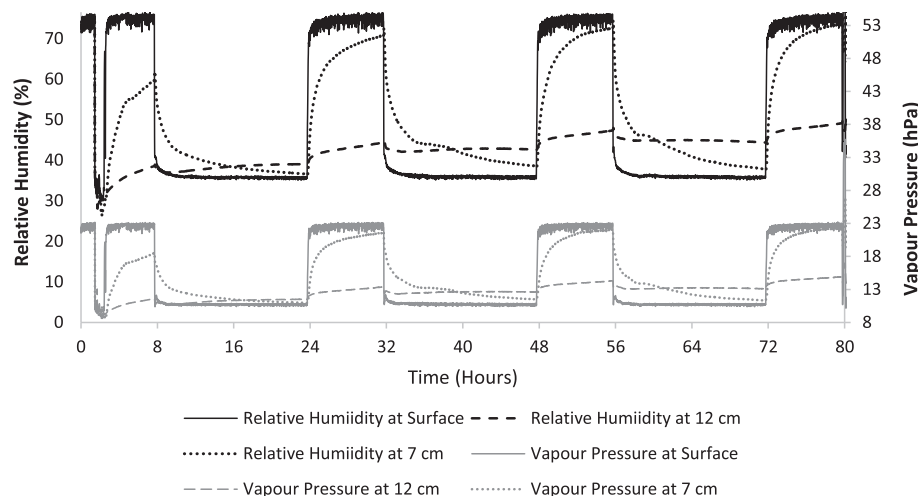


Fig. 15. The relative humidity and vapour pressure response at 7 cm and 12 cm depth of two hemp-lime samples.

lime is utilised in the assembly incorporating plasterboard. On the other hand, it is plausible that the moisture buffering capacity of hemp-lime is under-utilised or unutilised in the assembly incorporating wood wool boards because of the materials inherent moisture buffer capacity. When a trade paint was applied as a surface finish, the changes in MBV values of the assemblies were insignificant except for Assembly 2 where significant decrease in the MBV value was observed. It was further observed that the decrease in buffer value could be minimised by applying clay based paint instead of trade paint.

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